COMPARATIVE STUDY ON THE PERFORMANCE OF A TUBULAR SOLID OXIDE FUEL CELL FUELLED BY AMMONIA AND HYDROGEN

S. A. Hajimolana[1], M. A. Hussain[1,a], W. M. A. Wan Daud[1]

[1]Authors affiliation: University of Malaya

Address:

Chemical Engineering Department, Faculty of Engineering, University of Malaya, Kuala Lumpur, Malaysia

Email address: [a] mohd_azlan@um.edu.my

ABSTRACT

In this work, a dynamic model of a cathode-supported ammonia fed-tubular solid oxide fuel cell (NH_3-SOFC) is developed and presented. The model accounts for processes such as diffusion, inherent impedance, transport (heat and mass transfer), electrochemical phenomena, activation and concentration polarizations for anode and cathode, as well as ammonia decomposition. The performance of NH_3-SOFC is compared to that of H_2-SOFC, it is found that with the same inlet values for both SOFCs under similar conditions, the performance of the cathode-supported NH_3-SOFC is much higher than that for the H_2-SOFC.

Keywords- NH_3-SOFC; H_2-SOFC; efficiency; ammonia decomposition

INTRODUCTION

Solid oxide fuel cells (SOFCs) have shown promise in the electricity generating sector for stationary applications in the mid-term future (Stambouli and Traversa, 2002). This is due to the fact that the energy efficiency usually achieved in a SOFC is much greater than that obtained from conventional heat engines or any other types of fuel cells. Furthermore, additional efficiency may be gained by adding a bottoming cycle to recover heat from hot gases exhausted from a SOFC (Suwanwarangkul et al., 2003).

SOFCs can generate electricity at high fuel efficiencies (typically in the range of 35-80%). Such high efficiencies are a significant competitive advantage over other technologies. In addition, SOFCs offer high power density, low cost, scalability, fuel flexibility, and superior durability.

One of the most glowing advantages of SOFCs over other types of fuel cells is that a variety of fuels can be fed into the SOFC (Hajimolana et al., 2011). Although hydrogen (H_2) is usually considered as an ideal fuel for fuel cells and the performance of H2- fuel cells is quite good, effective and economical production and storage of hydrogen as well as its refuelling infrastructure are still facing major challenges (Ni et al., 2008b). It is therefore important to use alternative fuels in SOFCs such as bio fuels and ammonia. Ammonia is a good hydrogen carrier, and might be an excellent substitute for hydrogen and hydrocarbons for the reasons given below. Firstly, the price of ammonia is as competitive as that of hydrocarbons. Secondly, ammonia can be easily liquefied under about 10 atm at ambient temperatures or at −33 ◦C under atmospheric pressure, and the volumetric energy density of liquefied ammonia is about 9×106 kJm−3, which is higher than that of liquid hydrogen, making it useful for transportation and storage. Thirdly, ammonia is less flammable compared with the other fuels and the leakage of ammonia can easily be detected by the human nose under 1 ppm. Fourthly, and most importantly,

there are no concerns about anode coking, since all the by-products of the electrode reaction are gaseous (Ma et al., 2006). All of the above imply that ammonia could be an ideal candidate as a liquid fuel for SOFCs, at least at the present stage when the coking problem of hydrocarbon fuels has not yet been resolved.

Although much experimental work has been done on ammonia-fuelled solid oxide fuel cell (NH_3-SOFC) [5-14], only few research studies are available on mathematical modelling of NH3-SOFC (Ni et al., 2008b, Ni, 2011, Ni et al., 2008a, Farhad and Hamdullahpur). Ni et al. (Ni et al., 2008b) developed an electrochemical model for studying the ammonia (NH_3)-fed solid oxide fuel cells with proton-conducting (SOFC-H) and oxygen ion-conducting electrolytes (SOFC-O). The effects of temperature and electrode porosity on concentration overpotentials have been studied in order to identify possible methods of improvement of SOFC performance. An electrochemical model has also been developed to predict the current density–voltage (I–V) characteristics of the NH_3-fed SOFC-H (Ni et al., 2008a). All overpotentials have been included in the electrochemical model. The performance of the H_2-fed SOFC-H has also been investigated for comparison. Ni (Ni, 2011), based on previous models, presented a 2D thermo-electrochemical model to investigate the heat/mass transfer, chemical (ammonia thermal decomposition) and electrochemical reactions in a planar SOFC running on ammonia. Simulations were conducted to study the complicated physical-chemical processes in NH_3-fueled SOFCs. The effects of operating potential and inlet gas velocity on NH_3-fueled SOFC performance were investigated. It was found that an increase in inlet gas velocity from 1 m/s to 10 m/s slightly decreased the SOFC performance and did not affect the temperature field significantly. For comparison, decreasing the gas velocity to 0.2 m/s was more effective in reducing the temperature gradient in the SOFC.

In this work a dynamic model of an ammonia fed-tubular solid oxide fuel cell that is based on first principles is developed and presented. The model accounts for processes such as diffusion, inherent impedance, transport (heat and mass transfer), electrochemical phenomena, anode/cathode activation and concentration polarizations as well as ammonia decomposition. The fuel cell performance on being fed with ammonia (NH_3-SOFC) is compared with the system that is fed with hydrogen (H_2-SOFC).

MODEL DESCRIPTION

The mathematical model used in this study was previously developed by this research group (S.Ahmad Hajimolana, 2009). The tubular SOFC system under study here is a bank of single tubular SOFCs. Each cell has two tubes, an outer tube and an inner tube, as shown in Fig. 1. The outer tube is a cell tube. The outer surface of the outer tube is the anode side of the cell, and its inner surface is the cathode side. Between the anode and cathode sides (surfaces) lies the solid oxide electrolyte. The inner tube is an air injection and guidance tube, composed of alumina, from which preheated air is injected into the bottom of the cell tube and flows over the cathode surface of the cell tube through the gap between the injection and the tubes. Fuel gas flows over the anode surface through the gap among the cell tubes.

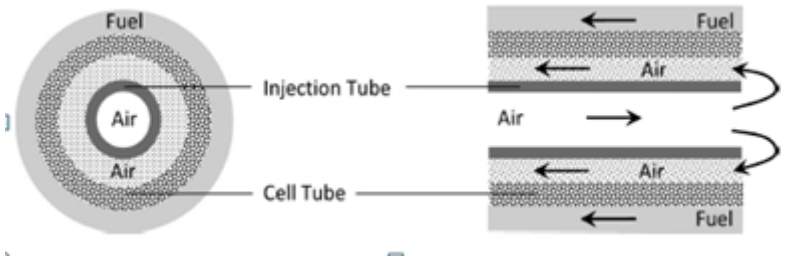

Fig. 1: Front and side views of a single tubular SOFC.

To develop a first-principles model of the SOFC system, a single tubular fuel cell is considered and divided into five subsystems (Hajimolana et al. 2011) : Subsystem 1 (SS1): air inside the injection tube; Subsystem 2 (SS2): injection tube; Subsystem 3 (SS3): air inside the space between the cell and injection tubes; Subsystem 4 (SS4): cell tube; and Subsystem 5 (SS5): fuel flow channel. The subsystems are shown in Fig. 2.

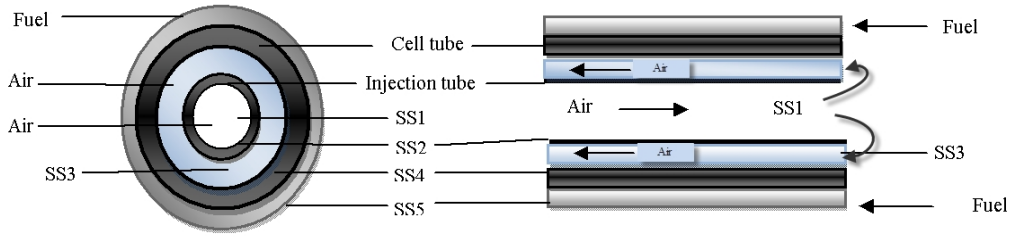

Fig. 2: Division of the single tubular SOFC into five subsystems

The fuel cell model is derived by writing mass, energy, and/or momentum conservation equations for each of the seven subsystems. The assumption considered in the mathematical formulation is that the gas boundary layers are very small relative to the corresponding radius; therefore, the equations governing the diffusion processes are written in the Cartesian coordinates. Fluid velocities are averaged along the radial direction. Partial pressures, temperatures, and fluid velocities in each subsystem are uniform in every direction. Specific properties such as conductivities, heat capacities, viscosities, and densities in each subsystem are uniform. Furthermore, outlet partial pressures, temperatures, and velocities are equal to the pressures, temperatures, and velocities inside the subsystem. The external load (load impedance) of the cell is a pure resistance. The conductivity of electrolyte (and electrodes) was neglected in this model because it was assumed that the thicknesses of the electrolyte (and electrodes) are very thin.

The mass/momentum and energy balance inside SS1, SS3 and SS5 are given as follows, respectively:

$$L\frac{d\xi^i_j\rho^i_j}{dt} = u^i_{j_{in}}\xi^i_{j_{in}}\rho^i_{j_{in}} - u^i_j\xi^i_j\rho^i_j + \sum N_j M_j\left(\frac{2r_i L}{r_i^2 - r_0^2}\right) + nr_j \tag{1}$$

$$L\frac{d(u_i\rho_i)}{dt} = (u_{i_{in}})^2\rho_{i_{in}} - (u_i)^2\rho_i + \frac{\rho_{i_{in}}R^*T_{i_{in}}}{M_i} - \frac{\rho_i R^*T_i}{M_i} \tag{2}$$

$$L\frac{d(\tilde{H}^i_j\rho^i_j)}{\partial t} = \rho^i_{j_{in}}u^i_{j_{in}}H^i_{j_{in}} - u^i_j\rho^i_j\tilde{H}^i_j + \frac{2Lh_w}{r}\left(T_w - T^i_j\right) \tag{3}$$

i is air flow injection tube, air flow inside cathode side, fuel flow inside anode side, *j* is air, oxygen, nitrogen, ammonia, hydrogen, *w* is the wall, N_j is mass transfer by means of diffusion, *n* is the molar number and r_j is producing or consuming of the components.

This model assumes that the pressure drop caused by the pipe resistance over the distance L is negligible. It is also assumed that energy is transferred to the flow streams by convection only. Enthalpy of formation, heat capacities, viscosities, and conductivities of the components of air and the fuel are given in a previous work (S.Ahmad Hajimolana, 2009).

Energy balance for the solid parts (SS2 and SS4) leads to:

$$m_s \tilde{C}_{p_s} \frac{dT_s}{dt} = \frac{\sigma 2\pi rL}{R_{rad}}\left(T_w^4 - T_j^4\right) + 2\pi rLh_w(T_j^i - T_w) + 2\pi rLh_w\left(T_j^i - T_w\right) + \sum H_j N_j \begin{pmatrix} 2r\ L \\ \frac{i}{r^2 - r^2} \\ i \quad 0 \end{pmatrix} +$$

$$2r_{ct_o} LR_{NH_3} \Delta H_{R_{NH3}} - 0.001 V_{out} I$$

(4)

The last three parts are heating transfer by means of diffusion, heating consuming by ammonia decomposition and heating supply by electrochemical reaction, respectively only in SS4.

Electrochemical model

Electrochemical reaction occurs inside the fuel cell (SS4) at the triple phase boundary (TPB), which as a result produces voltage and current. At the cathode side oxygen ions (with a negative charge) migrate through the crystal lattice. The oxygen is supplied, from air, at the cathode. H_2 in the fuel stream, diffuses into the anode side and reacts at the TPB with oxide ions (O2-) from the electrolyte to produce water. The electrons pass outside the fuel cell, through the load, and back to the cathode, where oxygen from the air receives the electrons and is converted to oxide ions, which are then injected into the electrolyte. The SOFC electrochemical reactions inside the TPB are:

$$Anode\ Side\ Ractions \begin{cases} H_2 + O^{2-} \longrightarrow H_2O + 2e \end{cases}$$

$$Cathode\ Side\ Reaction \begin{cases} O_2(g) + 4e \longrightarrow 2O^{2-} \end{cases}$$

Fuel cell voltage output is dependent on gas partial pressures and is adversely affected by concentration, activation, and ohmic losses (polarizations or irreversibilities). The electromotive force, reversible open-circuit cell voltage (denoted by E_{rev}) is given by the Nernst equation:

$$E_{rev} = E^0 + \frac{R_J T_{ct}}{2F} \ln\left[\frac{P_{H_2}^{TPB}(P_{O_2}^{TPB})^{1/2}}{P_{H_2O}^{TPB}}\right]$$

However, the actual cell voltage (*E*) is less than its theoretical open circuit voltage because it is strongly affected by several irreversible losses including activation losses due to irreversibility of electrochemical reactions at the three-phase boundary (TPB), concentration losses due to mass transport resistance in the electrodes (especially for thick anodes as in an anode-supported SOFC) and ohmic losses due to ionic and electronic charge transfer resistances. Actual voltage is thus given by:

$$E = E^o - \eta_{act_{ano}} - \eta_{conc_{ano}} - \eta_{act_{cat}} - \eta_{conc_{cat}} - \eta_{ohm}$$

An approximate equivalent circuit of an SOFC that consists of two internal resistances and one internal capacitance can be found in a separate work (Qi et al., 2005). According to the equivalent circuit approximation, the cell outlet voltage is governed by

$$\frac{dV_{tl}}{dt} = \left(\frac{1}{R_{tct}C_{ct}}\right)E - \frac{1}{C_{ct}}\left(\frac{1}{R_{tct}} + \frac{1}{R_{to}+R_{load}}\right)V_{tl} \tag{5}$$

$$V_{out} = \left(\frac{R_{load}}{R_{to}+R_{load}}\right)V_{tl}$$

$$I = \left(\frac{1}{R_{to}+R_{load}}\right)V_{tl}$$

where Rto is the total ohmic resistance in the inherent impedance of the cell, Rtct is the total charge transfer resistance of the cell, C_{ct} is the charge transfer capacitance of the cell, I is the current through the external resistive load, V_{out} is the fuel cell output voltage (voltage across the external load), and V_{tl} is the voltage across the total ohmic resistance and the load resistance in series.

Reaction of decomposition of ammonia

The thermal decomposition of ammonia for hydrogen production in the porous anode is solved using the chemical model described as follows. NH_3 thermal decomposition takes place on the anode surface (fuel) channel (SS4) as this process is favored at high temperatures. In the present study, it is considered that thermal decomposition can take place in the composite anode of the SOFC with typical catalyst (Ni) loading (Meng et al., 2007):

$$NH_3 \rightarrow 1.5H_2 + 0.5N_2$$

$$r_{NH_3} = z_r \exp\left(-\frac{E_r}{R_{kj}T_{ct}}\right)P_{NH_3}$$

where P_{NH3} is the partial pressure of NH_3. It's considered that the reaction rate is mainly dependent on the partial pressure of NH_3 and the operating temperature.It is assumed here that NH_3, H_2O and N_2 diffuse into the anode at a negligible rate; only H_2 gas diffuses into the anode (subsystem 4 (SS4)) (Ni et al., 2008a).

Fuel cell efficiency

In this work, the performance of the solid oxide fuel cell is evaluated in terms of the power density and thermal efficiency. The thermal efficiency is calculated by using the equation:

$$efficiency = \frac{P}{\Delta H_{fuel}} \times 100\%$$

where P and ΔH_{fuel} represent the electrical power generated by SOFC and enthalpy or thermal energy supplied at the fuel channel inlet, respectively.

In the temperature range of 600-1200 K, the thermal energy demand for the NH_3 decomposition reaction can be approximately calculated as (Ni),

$H_R = 40265.095 + 24.23214T_{ct} - 0.00946T_{ct}^2$

Model Equations for the Cathode and Anode-Side Diffusion Layer in subsystem 4 (SS4)

A mole balance on oxygen inside the cathode-side diffusion layer yields

$$\frac{\Delta_{cat}}{R}\frac{d}{dt}\left[\frac{P_{O_2}^{TPB}}{T_{ct}}\right] = N_{O_2} - \left(\frac{1}{2\pi r_{ct_i} L}\right) R_{O_2} \tag{6}$$

Mole balances on hydrogen and water vapor inside the anode-side diffusion layer yield are given as follow

$$\frac{\Delta_{ano}}{R}\frac{d}{dt}\left[\frac{P_{H_2O}^{TPB}}{T_{ct}}\right] = -N_{H_2O} + \left(\frac{1}{2\pi r_{ct_O} L}\right) R_{H_2O} \tag{7}$$

$$\frac{\Delta_{ano}}{R}\frac{d}{dt}\left[\frac{P_{H_2}^{TPB}}{T_{ct}}\right] = N_{H_2} - \left(\frac{1}{2\pi r_{ct_O} L}\right) R_{H_2} \tag{8}$$

The rates of consumption of hydrogen and oxygen by the electrochemical reactions to generate an electric current of I are given by

$$R_{H_2} = \left(\frac{1}{2F}\right) I \quad , \quad R_{O_2} = \left(\frac{1}{4F}\right) I$$

The consumption of the reactants is accompanied by the production of water at the following rate:

$$R_{H_2O} = -\left(\frac{1}{2F}\right) I$$

SIMULATION RESULTS AND DISCUSSION

Model validation

The dynamic model of the SOFC system derived in the previous section has 20 first order ordinary differential equations, which are integrated numerically using MATLAB. Simulation was done to compare the results with the experimental data of Singhal (Singhal, 2000). Because in this work the value of SOFC design was clear. In this simulation, the values of fuel and air flow rates were adjusted to match the values of factors given by Singhal (Singhal, 2000). The current–potential plot obtained from this

simulation was compared with the experimental data and the predictions from the model developed by Ota and co-workers (Ota et al., 2003) as shown in Fig. 4. The present model could predict the experimentally observed dependence of current density on cell potential very well at 890–960°C. Excellent agreement was also obtained in the low current density region in comparison to the model developed by Ota et al. (Ota et al., 2003) which actually showed some deviation from experimental results. As expected, higher current densities led to lower cell potentials due to the increase in activation, ohmic and concentration overpotentials. After validating the mathematical model developed in this work with experimental results of Singhal (2000) for H_2-SOFC, the model was improved to account for NH_3-SOFC. The novelty of the improved model was that it also accounted for the ammonia decomposition reaction, the heating consumed by this reaction and the anodic and cathodic concentration polarizations for a tubular NH_3-SOFC.

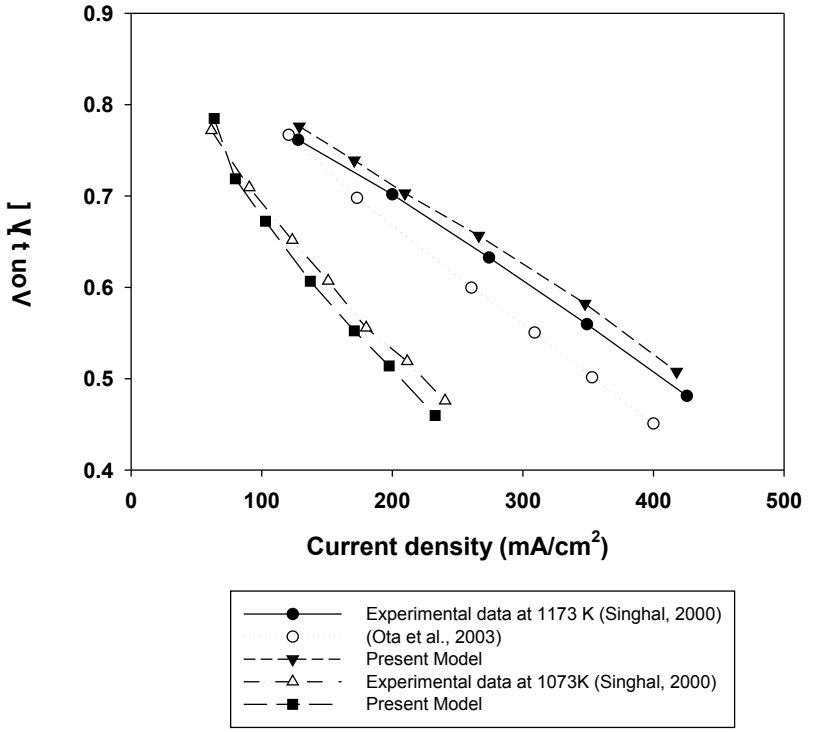

Fig. 4: Comparison of current–potential plots from the present model, model from Ota et al. (Ota et al., 2003) and the experimental data available in the literature (Singhal, 2000)

Comparison of SOFC efficiency between NH_3-fed SOFC and H_2-fed SOFC

One of the most brightened advantages of solid oxide fuel cells over other counterparts is its flexibility in the use of a variety of fuels such as natural gas, diesel, gasoline and alcohol without the need to reform the fuel into pure hydrogen. However, it is vital to use a fuel with higher efficiency and lower cost. The effect of fuel flow pressure and temperature on the performance of NH3-SOFC and H2-SOFC is compared. It is shown clearly in Fig. 5 that with the same inlet values for both SOFCs and same conditions, the performance of NH3-SOFC is much higher than H2-SOFC. It can be observed that at 1 atm. of the fuel pressure, the efficiency of NH3-SOFC and H2-SOFC is 44.83% and 38.48%, respectively. This is because at the same conditions, the molarity of hydrogen produced by ammonia decomposition is 1.5 times more than H2-SOFC.

Therefore, more hydrogen concentration makes the rate of electrochemical reaction faster, resulting in higher voltage, current and fuel cell power. At the 1 atm of the fuel flow pressure, the inlet molar fraction of hydrogen in H2-SOFC is 0.85 and the inlet molar fraction of hydrogen in NH3-SOFC is 0.97. That's why the concentration of hydrogen in NH3-SOFC is higher than H2-SOFC. Therefore, the efficiency of NH3-SOFC at 1 atm is higher than H2-SOFC.

It is illustrated in Fig. 6 that the cell tube temperature of NH_3-SOFC is ~20 K lower than H_2-SOFC because the ammonia decomposition is an endothermic reaction. The lower operating temperature increases the range of materials that can be used to construct the device (including metals), increases material durability and overall product robustness and crucially lowers cost. This result shows that it is possible to operate the tubular SOFC at temperatures below 800 °C when it is fed with ammonia. Moreover, it is found that NH_3-SOFC can take 30 s less than H_2-SOFC to adjust to load change. These results reveal that ammonia can be a suitable replacement fuel for hydrogen in the SOFC.

Clearly it is shown in Fig. 7 that the H_2-SOFC efficiency increases dramatically when the fuel flow temperature increases while that for the NH_3-SOFC is almost the same. This shows that the effect of fuel flow temperature on H_2-SOFC is much more significant than NH_3-SOFC. In case of H_2-SOFC higher fuel flow temperature increases the cell temperature and the rate of electrochemical reaction also increases. However, the case for NH_3-SOFC is different. A higher fuel flow temperature causes higher ammonia decomposition which is endothermic, thus reducing the cell temperature, thereby decreasing the rate of the electrochemical reaction. Therefore the fuel cell performance decreases slightly.

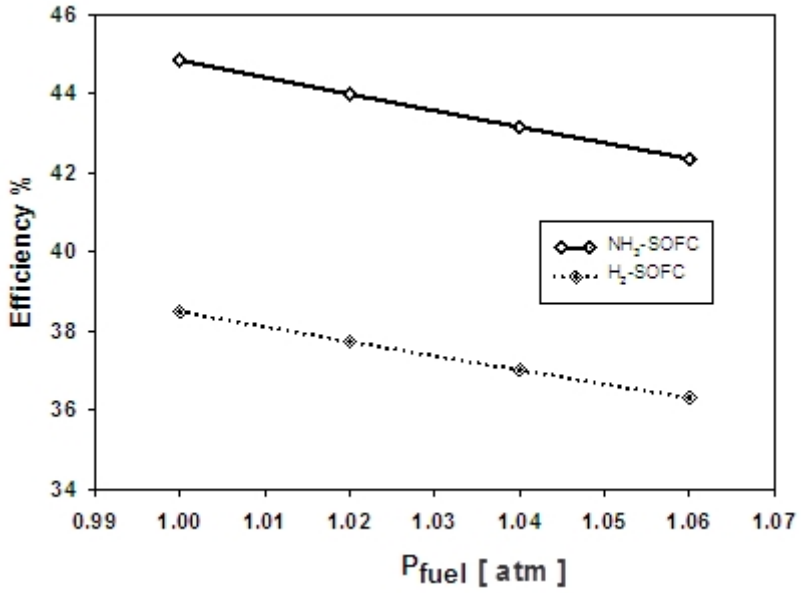

Fig. 5: Comparison of NH_3-SOFC and H_2-SOFC efficiency when the fuel flow pressure changes

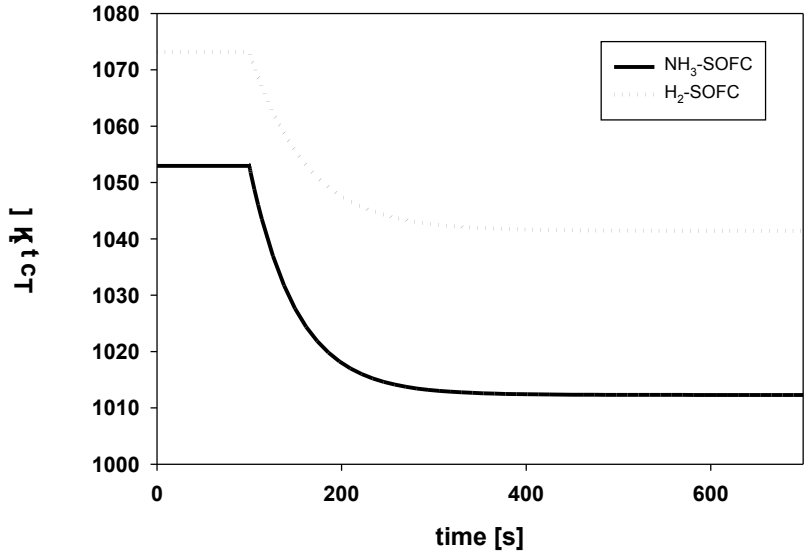

Fig. 6: Comparison of NH_3-SOFC and H_2-SOFC temperature when the fuel flow pressure changes from 1 atm to 1.5 atm.

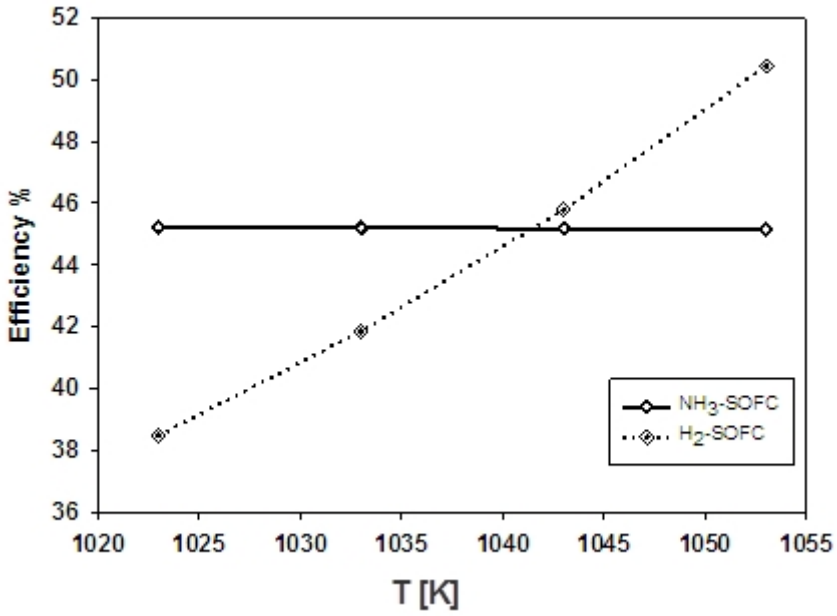

Fig. 7: Comparison of NH_3-SOFC and H_2-SOFC efficiency when the fuel flow temperature changes.

CONCLUSION

The mathematical model developed in this study has been verified with previous experimental results and modelling studies. The results obtained here are comparable or better than those reported earlier. The performance of the NH_3-SOFC is compared with that of the H_2-SOFC. It is found that with the same inlet values for both SOFCs under similar conditions, the performance of NH_3-SOFC is higher than that of the H_2-SOFC. Moreover, it is observed that NH_3-SOFC can take 30 s less time than the H_2-SOFC to adjust to load changes. It is found that inlet fuel flow pressure has almost the same influence on fuel cell performance while the effect of fuel temperature on both NH_3-

SOFC and H_2-SOFC is different. The impact of fuel flow temperature by means of load changes on the efficiency of the H_2-SOFC is more than the efficiency of the NH_3-SOFC.

NOMENCLATURE

C_{ct} = charge transfer capacity (F; note that 1 F= 1 A s/V)

$\bar{C}_p$ = specific heat capacity at constant pressure (kJ/ (kg K))

$\bar{C}_v$ = specific heat capacity at constant volume (kJ/ (kg K))

E_{rev} = reversible cell voltage (V)

E = irreversible cell voltage (V)

h = convective film heat-transfer coefficient (kJ/ (s m^2 K))

$\bar{H}$ = enthalpy of formation (kJ/ kg)

I= cell current (A)

L = length of the tubular fuel cell (length of the cell and injection tubes) (m)

m = mass (kg)

M = molecular weight (kg/kmol)

N = rate of mass transfer (kmol/(s m^2))

p = partial pressure (atm)

P = total pressure (atm)

r = radius (m)

R = universal gas constant; R= 8.20575× 10^{-2} m^3 atm/ (K kmol)

R^* = universal gas constant; R^* = 8.31447× 10^3 m^2 kg/ (K kmol s^2)

R_J = universal gas constant; R_J=8.31447× 10^3 J/ (K kmol)

R_{kJ} = universal gas constant; R_{kJ}=8.31447 kJ/ (K kmol)

R_{tct} = total charge transfer resistance (Ω)

R_{load} = external load resistance (Ω)

R_{to} = total ohmic resistance (Ω)

R_{rad} = radiation heat transfer resistance

R_{NH3} = rate of ammonia decomposition (kmol/ s m^2)

R_{H2} = rate of consumption of H_2 (kmol/ s)

R_{H2O} = rate of consumption of H_2O (kmol/ s)

R_{O2} = rate of consumption of O_2 (kmol/ s)

T = temperature (K)

u = fluid velocity

V_{out} = fuel-cell outlet voltage (V)

z_r = frequency factor of the ammonia decomposition (kmol/ $atm^{0.5}$ m^2 s)

Greek Letters

Δ = thickness of the diffusion layer

ρ = density (kg/m^3)

ζ =mole fraction

η= polarization loss

Subscripts

ano= anode

act= activation

cat= cathode

ct = cell tube

conc= concentration

o = outer

i = inner

in = inlet

s= solid

out = output

REFERENCES

FARHAD, S. & HAMDULLAHPUR, F. Conceptual design of a novel ammonia-fuelled portable solid oxide fuel cell system. *Journal of Power Sources,* 195**,** 3084-3090.

HAJIMOLANA, S. A., HUSSAIN, M. A., DAUD, W. M. A. W., SOROUSH, M. & SHAMIRI, A. (2011) Mathematical modeling of solid oxide fuel cells: A review. *Renewable and Sustainable Energy Reviews,* 15**,** 1893-1917.

MA, Q., PENG, R., LIN, Y., GAO, J. & MENG, G. (2006) A high-performance ammonia-fueled solid oxide fuel cell. *Journal of Power Sources,* 161**,** 95-98.

MENG, G., JIANG, C., MA, J., MA, Q. & LIU, X. (2007) Comparative study on the performance of a SDC-based SOFC fueled by ammonia and hydrogen. *Journal of Power Sources,* 173**,** 189-193.

NI, M. Thermo-electrochemical modeling of ammonia-fueled solid oxide fuel cells considering ammonia thermal decomposition in the anode. *International Journal of Hydrogen Energy,* 36**,** 3153-3166.

NI, M. (2011) Thermo-electrochemical modeling of ammonia-fueled solid oxide fuel cells considering ammonia thermal decomposition in the anode. *International Journal of Hydrogen Energy,* 36**,** 3153-3166.

NI, M., LEUNG, D. Y. C. & LEUNG, M. K. H. (2008a) Electrochemical modeling of ammonia-fed solid oxide fuel cells based on proton conducting electrolyte. *Journal of Power Sources,* 183**,** 687-692.

NI, M., LEUNG, D. Y. C. & LEUNG, M. K. H. (2008b) Mathematical modeling of ammonia-fed solid oxide fuel cells with different electrolytes. *International Journal of Hydrogen Energy,* 33**,** 5765-5772.

OTA, T., KOYAMA, M., WEN, C.-J., YAMADA, K. & TAKAHASHI, H. (2003) Object-based modeling of SOFC system: dynamic behavior of micro-tube

SOFC. *Journal of Power Sources,* 118**,** 430-439.

QI, Y., HUANG, B. & CHUANG, K. T. (2005) Dynamic modeling of solid oxide fuel cell: The effect of diffusion and inherent impedance. *Journal of Power Sources,* 150**,** 32-47.

S.AHMAD HAJIMOLANA, M. S. (2009) Dynamics and Control of a Tubular Solid-Oxide Fuel Cell. *Ind. Eng. Chem,* 48**,** 6112-6125.

SINGHAL, S. C. (2000) Advances in solid oxide fuel cell technology. *Solid State Ionics,* 135**,** 305-313.

STAMBOULI, A. B. & TRAVERSA, E. (2002) Solid oxide fuel cells (SOFCs): a review of an environmentally clean and efficient source of energy. *Renewable and Sustainable Energy Reviews,* 6**,** 433-455.

SUWANWARANGKUL, R., CROISET, E., FOWLER, M. W., DOUGLAS, P. L., ENTCHEV, E. & DOUGLAS, M. A. (2003) Performance comparison of Fick's, dusty-gas and Stefan-Maxwell models to predict the concentration overpotential of a SOFC anode. *Journal of Power Sources,* 122**,** 9-18.

BRIEF BIOGRAPHY OF PRESENTER

I AM SEYEDAHMAD HAJIMOLANA as a presenter, studying in the University of Malaya in PhD program. I have two publications in the field of SOFC modelling:

* S. Ahmad Hajimolana, Mohd Azlan Hussain, Wan Mohd Ashri Wan Daud, Masoud Soroush, A. Shamiri, Mathematical Modeling of Solid Oxide Fuel Cells: a review, Journal of Renewable and Sustainable Energy Reviews, 15 (2011) 1893–1917.

* S. Ahmad Hajimolana, Masoud Soroush, Dynamics and Control of a Tubular Solid-Oxide Fuel Cell. Ind. Eng. Chem. Res. 2009, 48, 6112–6125.